Journal of Civil Engineering and Materials Application
Journal home page: http://jcema.com

Received: 09 October 2023 • Revised: 21 November 2023 • Accepted: 03 January 2024

Research

doi:10.22034/jcema.2024.436968.1131

Behavior OF Low-Carbon Rice Husk Ashin Cement Mortar Under Compressive Loading

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ABSTRACT

This study explores the impact of low carbon Rice Husk Ash (RHA) on the rheological and mechanical properties of mortar. RHA, sourced from Nigeria, underwent chemical analysis to ascertain its pozzolanic activity index. Rheological tests conducted on the mortar included standard consistency, initial and final setting times, as well as fresh density of mortar. While mechanical properties such as compressive, tensile, and flexural strength were assessed. Ordinary Portland Cement (OPC) was partially substituted with RHA at varying intervals with 0% RHA serving as the control. Compressive strength was measured after 7, 14, and 28 days of water curing, while tensile and flexural strength were evaluated at the 28th day. The water-to-binder ratio was fixed at 4.85, and binder-to-fine aggregate ratios of 1:2.36 and 1:2.76 were employed. RHA was classified as Class N, indicating high pozzolanic capacity. Results revealed increased consistency, initial and final setting times and a decreased density with RHA addition. The peak compressive strength was observed at 10% RHA, reaching 8.759 and 10.252 MPa for mix ratios 1:2.75 and 1:2.36, respectively. Moreover, at 10% RHA, flexural and tensile strength for mix ratio 1:2.36 exceeded those of plain mortar by 22.5% and 9.6%, respectively. In conclusion, the study highlights the significant role of RHA as a pozzolanic material in enhancing cementitious reactions in mortar systems, though the influence of RHA particle size was not considered.

Keywords: **Pozzolans, Compressive strength, Tensile strength, Mortar, Flowability**

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1. INTRODUON

Rice is a significant food in the global market space and the second most produced grain in the world. Corn, the largest grain, is produced for various reasons as opposed to rice which is produced primarily for consumption. The leading region of the world which produces rice is Asia,

particularly South-East and East Asia; the reason for their dominance is because their regions are vastly tropical in nature. About 20% of rice paddy is made up of rice husks. The current global production of rice paddy is approximately 500 million tons, resulting in the production of 100 million tons of rice husks [1]. The current rice production rate globally stands at 700 million tons per year, with Africa accounting for about 18 %. China and India are the top producers of rice paddy. However, according to FAO report, Nigeria is the largest producer of rice in Africa.

Rice husk is a byproduct obtained from the milling of rice grains. It is also the outer covering of the rice grain. Rice husks, being organic in nature contains approximately 40 % Cellulose, 30 % Lignin and 20 % Silica. Rice husk can absorb water ranging from 5 % to 16 %. It is responsible for approximately 30 % of the overall weight of a rice grain. Bulk density is low and lies within the range of 90 -150 Kg/m^3. After removing the husk during the milling process of rice grains, what remains is typically the rice grain with a thin brown layer. Upon further milling, the brown layer is removed resulting in palatable white rice. The Rice husk when incinerated results to rice husk ash (RHA).

RHA is pozzolanic in nature due to the presence of silica and its fine particle size. The degree of pozzolanic activity of husk ash depends on the silica content and fineness of the material. Calcination Temperature also plays a role in achieving a high pozzolanic activity, as Jimoh et al. [2] recommend a temperature between 700 -800 ^0C for optimal reaction of the RHA with lime ($Ca(OH)_2$). When rice husk is calcined at a controlled temperature of 500-800°C until total combustion, the resulting ash exhibits a whitish and fine appearance, indicative of its physical transformation. At this temperature range, the rice husk ash (RHA) becomes non-crystalline and low in carbon content. Research indicates that this type of ash has a significantly positive pozzolanic effect in concrete, unlike low-carbon concrete [3-5]. In contrast, when the calcination temperature is low, a significant amount of un-calcined and high-carbon ash is formed. This is often associated with open-field burning of the rice husk ash. According to ASTM C618 [6], it specifies that the loss on ignition (LOI), which includes both carbon and other volatile materials, for Class N pozzolans (which include RHA) should not exceed 5%. Indian Standard IS 1727:1967 [7] - Specification for Burnt Clay Pozzolana: This standard specifies that the total carbon content in burnt clay pozzolana (including RHA) should not exceed 5%. Habeeb and Mahmud [3] and Bakar et al. [8] also classified RHA with a carbon content below 5% as a low carbon ash. Additional benefits include the usage of the RHA as a biomass fuel. The silica is also used economically as a substitute for micro silica fume/silica fumes in concrete production. Additionally, it serves as absorbents for oil and chemicals, a source of silicon, insulation powder in steel mills, repellent in the form of 'vinegar tar,' release agent in the ceramic industry, insulation material for homes and refrigerants, and as soil ameliorants.

A pozzolanic reaction occurs when a Siliceous or an aluminous material comes in contact with calcium hydroxide ($Ca(OH)_2$) or lime in the presence of water to form calcium silicate hydrate (C-S-H) which is cementitious in nature [9]. The C-S-H is released in the form of tri-calcium silicate (C_3S) and di-calcium silicate (C_2S). Other components that are released during the wetting process include calcium hydroxide ($Ca(OH)_2$, C_3A and C_4AF as indicated in equation 1. The C, S, A and F represents CaO, SiO_2, Al_2O_3 and C_4AF [10].

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2 \quad \ldots\ldots(1)$$

$$2(2CaO.SiO_2) + 4H_2O \rightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2 \quad \ldots\ldots(2)$$

$$3CaO.Al_2O_3 + 31H_2O + 3CASO_4 \rightarrow 3CaO.\ Al_2O_3.\ 3CaSO_4.\ 31H_2O \quad \ldots\ldots(3)$$

$$4CaO.Al_2O_3.Fe_2O_3 + 10H_2O + 2Ca(OH)_2 \rightarrow 6CaO.\ AI_2O_3.\ Fe_20_3.\ 12\ H_2O \quad \ldots\ldots(4)$$

The C-S-H gel,a reaction outputs in equation 1 and 2 is responsible for the bonding of the constituent materials. Calcium hydroxide and Ettringite ($3CaO.3CaSO_4.31H_2O$, equation 3) mainly consist of hydrated crystalline products that are randomly distributed and form the frame of the gel product. As indicated in equation 4, the C_4AF further reacts with $Ca(OH)_2$ resulting in the formation of additional gel products. Excess $Ca(OH)_2$ is also counterproductive to the area of durability performance of concrete [11].

Tobermorite gel:

SiO_2+ Ca $(OH)_2$+ H_2O → $CaO.SiO_2.H_2O$ ……(5)

Calcium aluminate hydrate:

Ca $(OH)_2$+ H_2O + Al_2O_3→$CaO.Al_2O_3.Ca(OH)_2.H_2O$ ……..(6)

Calcium aluminate ferrite hydrate:

Ca $(OH)_2$+ Fe_2O_3+ $A1_2O_3$+ H_2O → $Ca(OH)_2.Al_2O_3.Fe_2O_3.H_2O$ ……..(7)

This crystalline cementitious gel (C-S-H &C-A-H) hardens with time under various curing conditions thus resulting in formation of a denser cement paste [12]. Research conducted by Alireza et al. [10] show that the pozzolanic effect on mortars is observed during the later stages. Hence, a delay in the reaction at the early-stage results in a more porous and permeable concrete. However, the heat generated during hydration, which causes intrinsic thermal shrinkage in high and ultra-high strength mortars, is reduced with the inclusion of pozzolana. Also, at its initial stage of reaction, it acts as a precipitation site for the early formation of C-S-H and C-H.

From data collated by researchers, the amount of CH reduces in mortar paste after 3 days and reaches a zero percent at 90 days when combined with 30% RHA. Whereas, in the case of the reference paste, it increases with hydration time [10]. The inclusion of pozzolana decreases the quantity of CH and increases the amount of C-S-H formed. The formation of C-S-H produces a durable concrete of improved strength and density. The degree of its performance in concrete depends on the state of the ash (either crystalline or amorphous). Reports by Habeeb & Fayyadh [13] and Lin et al. [14] indicated better performance of amorphous ash in the presence of lime compared with crystalline ash. Approximately 85 to 95 % by weight of amorphous silica are produced when 1kg of RHA ash is burnt at a controlled temperature of 700 -800 ^{0}c [15]. The degree of the reaction with lime is also dependent on the specific surface area of the RHA. The finer the particle size, the better the performance in concrete [16], [10]. Feng et al. [17] attributed an increase in the early hydration of mortar to the specific surface area of RHA. However, the particle size of pozzolanas is less reactive than cement, they produce a large number of nucleation sites for the precipitation of the hydration products by dispersing in cement pastes; this creates a denser and a more homogenous paste [18]. Berry et al. [19] also documented that non-reactive pozzolana can act as void fillers in concrete. Cabrera & Rojas [20] observed that the pattern of pozzolanic reaction can be analyzed using the Jander diffusion equation based on Fick's parabolic law of diffusion assuming a spherical particle interface.

Mayooran, et al. [21] compared the use of open air burned low- and high - carbon rice husk ash as partial cement replacement in cement block production. Their findings revealed that cement blocks partially replaced with low-carbon RHA performed slightly better mechanically compared to those with high-carbon RHA. However, both were considered suitable for use in non-load-bearing masonry wall construction. Regarding density performance, both low- and high-carbon RHA resulted in a decrease when added to the cement. Water absorption was higher in high-carbon RHA cement blocks compared to those with low carbon. However, an overall increase in water absorption was noticed with RHA for both low- and high-carbon varieties. Mayooran et al. [21] investigated the impact of ground low-carbon rice husk on the microstructure and performance of concrete. They found that substituting 10% of cement with rice husk resulted in concrete with a peak compressive strength 15.6% higher than that of cement concrete without rice husk. This finding is consistent with the results reported by Tuleun et al. [22] regarding similar materials in concrete.

In addition to its use in mortar and concrete production, research has explored the potential of rice husk ash (RHA) for other construction purposes, including road soil stabilization. Ghavami et al. [23] examined the strength behavior of weak clayey soils when stabilized with a blend of RHA and cement. They found that the maximum unconfined compressive strength was achieved with a 10% inclusion of RHA, after which a decrease in strength was observed. A similar trend was observed in the California Bearing Ratio (CBR) test results. However, a study conducted by Barwar et al. [24] revealed that the maximum strength was attained at a 9% RHA replacement level.

Sanou et al. [25] investigated the mechanical behavior of mortars modified with rice husk ash, focusing on materials characterization (XRD pattern analysis and SEM analysis) and mechanical performance of the RHA cementitious mortars, particularly compressive and flexural strengths, over a 28-day curing period. Selvaranjan et al. [26] conducted similar research, focusing on material characterization, compressive strength, thermal conductivity, water absorption, density, porosity, and workability performance of cement mortar with RHA, with a specific curing age of 28 days. Jamil et al. [27] omitted the experimental investigation of the physical and chemical effects of RHA on the fresh properties of mortar, focusing instead on the microstructural characterization and compressive strength of RHA mortars. Danso H. [28] also conducted research on the mechanical behavior of rice husk ash (RHA) in mortars, without emphasizing the adopted calcination process. Although the researcher focused on the compressive and tensile characteristics of RHA-mortar at 7, 14, and 28 days, there was no analysis regarding the rheological and stress-strain behavior of RHA-mortar at various curing ages. Zakaria et al. [29] also investigated the workability and compressive strength behavior of cement mortar when incorporating RHA. However, their study focused solely on the workability and compressive strength of the mortars.

Our intended research aims to address gaps identified in the aforementioned works by investigating the mechanical behavior of RHA mortars at varying curing ages of 7, 14, and 28 days. This investigation seeks to understand the pattern of strength development and include an examination of tensile behavior. Based on their research, no investigation was conducted on the fresh property (Atterberg limit) behavior, which is an important parameter in concrete works. This research aims to bridge that gap by delving into the rheology of mortar systems embedded with RHA at varying percentages. Further research will also be conducted to understand the stress-strain behavior of the specimens incorporated with RHA.

The use of rice husk ash is known to have cementitious potential, primarily due to its high percentage of silica oxide when properly prepared. This silica oxide component enhances reaction in lime solution resulting to an improvement in strength and durability performance. Hence, there is a need to investigate the possibility of partially replacing cement mortar with RHA with the aim of achieving a more sustainable and eco-friendlier composite. Little research has been conducted on the use of rice husk ash calcined at a controlled temperature as pozzolana and filler in mortar production.

2. MATERIALS AND METHODS

2.1. Materials

Dangote's Ordinary Portland cement (42.5R) conforming to ASTM C150 [30] and rice husk ash were used as cementitious binders in the research program.The rice husk was obtained from a rice mill in Oja Gboro Ilorin, Kwara State, Nigeria. The collected rice husk was then converted into an amosphous ash by virtue of calcination of the husk in a furnace at a controlled temperature of 600°C for 6 hours; this process was carried out at the Institute of Technology (IOT) Ilorin, Kwara State, Nigeria. The RHA sample was then sieved through a 75um sieve to remove the coarse particles. The finer particles that passed through were used as an input parameter in the research work. The whitish RHA sample had a specific gravity of 2.08, fineness (≤ 75um) of 89%, density of 464.6 Kg/m3, and specific surface area of 35.98 m2/g. The chemical properties of rice husk ash and its pozzolanic activity index class are presented in Table 1. Also, from Table 1, the RHA falls within class N of the index, indicating its high pozzolanic potential in combination with Lime (Ca(OH)2).

Table 1. Chemical properties and pozzolanic activity index class of RHA

Chemical properties of RHA										
Elemental	SiO_2	Al_2O3	CaO	Fe_2O_3	MgO	Na_2O	SO3	K_2O	LOI	Ash
RHA	69.43	0.83	0.58	0.62	0.87	0.84	7.82	7.51	1.4	5.61

Chemical pozzolanic	**Class C**	**Class N**	**Class**	**Rice husk ash (RHA)**
SiO_2 + AlO_3 +Fe_2O_3 (%)	≥ 50	≥ 70	≥ 70	70.82
SO3	≤ 4	≤ 5	≤ 5	7.82
MgO	≤ 5	≤ 5	≤ 5	0.87
Loss of Ignition	≤ 6	≤ 10	≤ 2	1.4
Na_2O	≤ 1.5	≤ 1.5	≤ 1.5	0.84

Local river sand was used as a non-reactive fine filler material in the mix. As shown in Figure 1, the particle size distribution of fine aggregate was mainly between the 0-4mm sizes. The gradation of the fine aggregate was found suitable for all mixes since the fineness modulus is 4.525 (coarser), coefficient of uniformity Cu is 16.55 which is greater than 5, and the coefficient of curvature is 2.5 greater than 1 but less than 3 as stated in ASTM D6913 [31]. Therefore, the fine aggregate is classified as well graded fine sand. The fine aggregate also had an average silt content of 2.6 % which is less than 6% as prescribed in ASTM D4189 [32]; thus, the fine aggregate is suitable for all mix proportions. The relative density of the aggregates in oven dried and saturated-surface dried (SSD) states were 2.20 and 2.48; while its bulk density, void content and volume of measure were 1403.3 Kg/m^3, 36.21 % and 0.003 m^3respectively.

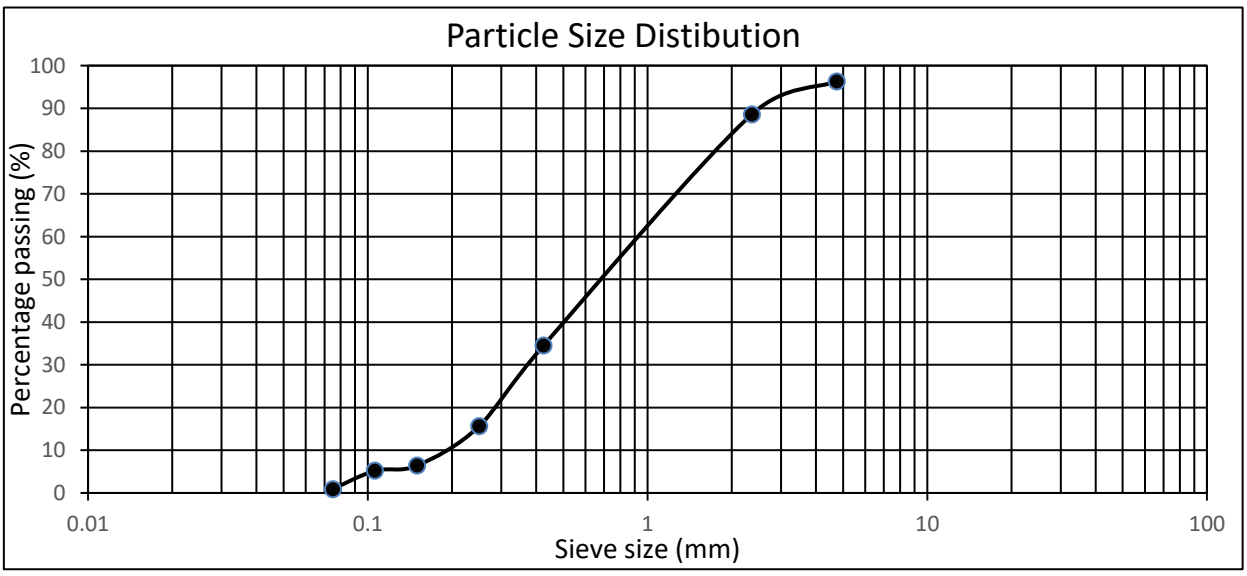


Figure1. Particle size distribution of fine (local river sand) aggregate

2.2. Mix proportion and curing

OPC was partially replaced with the pozzolanic RHA at varying intervals of 10, 20, 30 and 40 % by weight of OPC. OPC cementitious binders without RHA were used as the control. The water to binder ratio was set at 0.485. Binders-to-sand ratios of 1:2.75 and 1:2.36 were also adopted. Conplast SP(Polycarboxylate based ether) was used to enhance the flowability of the mix within a range of 100 –

115 %. The produced specimens were initially covered with damp proof membrane for 24 hours; after which, they were demoulded and cured in water at the various testing ages (7,14,28 days). The mortar mix proportions for the two binders-to-sand ratios of 1:2.75 and 1:2.36 are presented in Table 2 and 3, respectively.

Table 2. Mix proportion of the mortar containing RHA (1:2.75).

Percentage replacement (%)	Weight of water (g)	Weight of cement (g)	Weight of RHA (g)	Weight of sand (g)	SP (%)
0RHA	363.8	750	-	2063	1.2
10RHA	363.8	675	75	2063	2.0
20RHA	363.8	600	150	2063	3.6
30RHA	363.8	525	225	2063	4.2
40RHA	363.8	450	300	2063	5.1

Binder-to-sand ratio, 1:2.75; water-to-binder, 0.485.

Table 3. Mix proportion of the mortar containing RHA (1:2.36)

Percentage replacement (%)	Weight of water (g)	Weight of cement (g)	Weight of RHA (g)	Weight of sand (g)	SP (%)
0RHA	363.8	750	-	1770	0.9
10RHA	363.8	675	75	1770	1.6
20RHA	363.8	600	150	1770	3.5
30RHA	363.8	525	225	1770	3.9
40RHA	363.8	450	300	1770	4.6

Binder-to-sand ratio, 1:2.36; water-to-binder, 0.485.

2.3. Test for rheological properties of mortar (Consistency, initial and final setting time)

The rheological properties of the cementious mortar depend on the water requirement and flowability of the paste, which in turn determines the harden behavior of the paste at its latter stage. The degree of dispersion of the cement in water is also a key parameter in terms of the fresh and hardened performance of the paste. Hence, it imperative to study the water requirement and setting time (initial and final) behavior of cementious paste when incorporated with RHA (at 10, 20, 30 and 40 % replacement levels). The Normal consistency of cement represents the percentage of water by weight of cement, which allows a plunger of 10 mm diameter to penetrate up to a depth of 5 mm to 7 mm above the bottom of a vicat mould. The outcome indicates the consistency limit of mortar.

For the Initial setting time of cement mortar, it is the period elapsing between the time when the water is added to cement and the time at which needle of 1 mm^2 section fails to pierce the test block to a depth range of 33-55 mm from the top of the mould. The final setting time is the period elapsing between the times when the water is added to the cement and the time at which the needle makes an impression on the paste while not causing the attachment to make an impression. Furthermore, the tests for consistency and the setting time (both initial and final) conformed to ASTM C187 [33] and ASTM C191 [34], respectively.

2.4. Fresh density (unit weight), yield, and air content (gravimetric) of fresh mortar

The scope of this test is to determine the fresh density, yield and air content of the control mix (without RHA) and binary mix at various percentages (10%, 20%, 30% and 40%RHA added to cement). The essence is to compare the densities with that of the control to determine whether lightweight mortar can be achieved. The test procedure was carried out in accordance with ASTM C138 [35].

2.4.1. Calculation

a) Density (unit weight):

The net mass of the mortar was calculated in kilograms by subtracting the mass of the measure, M_m, from the mass of the measure filled with mortar, M_c. Calculate the density, D, kg/m^3, by dividing the net mass of mortar by the volume of the measure, V_m as follows:

$D = (M_c - M_m)/V_m$…….(1)

b) Theoretical density:

Theoretical density was calculated as follows:

$T = M/V$ …… (2)

c) Yield: was calculated as follows:

$Y(m^3) = M/D$ …… (3)

d) Air Content – was calculated as follows:

$A = [(Y – V)/Y] \times 100$

Where:

D = density (unit weight) of mortar, kg/m^3,

M_c = mass of the measure filled with mortar, kg,

M_m = mass of the measure, kg,

V_m= volume of the measure, m^3,

T = theoretical density of the mortar computed on an air free basis, kg/m^3,

M = total mass of all materials batched, kg,

V = total absolute volume of the component ingredients in the batch, m^3,

Y = yield, volume of mortar produced per batch, m^3,A = air content (percentage of voids) in the mortar.

2.5. Test for mechanical properties of Mortar

2.5.1. Compressive strength

In this test, cubes specimens of sizes 50×50×50 mm (Length × Height × Thickness) were produced and measured for compressive strength. Four cube specimens were cast for each cement replacement percentage with RHA to maintain uniformity among them. They were then tested in a universal testing machine (UTM) at curing ages of 7, 14 and 28 days respectively. The loading rate of the machine was set at 0.001 m/s. The test procedure was conducted in accordance with ASTM C39/39M [36]. The average result of the 4 specimens was computed and documented.

2.5.2. Flexural strength

This test method was used to determine the flexural strength behavior of prepared beam specimens. The specimens of dimensions (length= 175 mm, width = 50 mm and thickness = 50mm) were produced using a mix ratio of 1:2.36. Prior to testing, the specimens were cured in water for a period of 28 days. The testing procedure conformed to C31/C31M [37]. Variations in specimen size, mode, compaction consistency, moisture condition, curing method, or whether the beam has been molded or sawed to size may result in varying flexural strength results. The setup of flexural strength testing is presented in Figure 2.

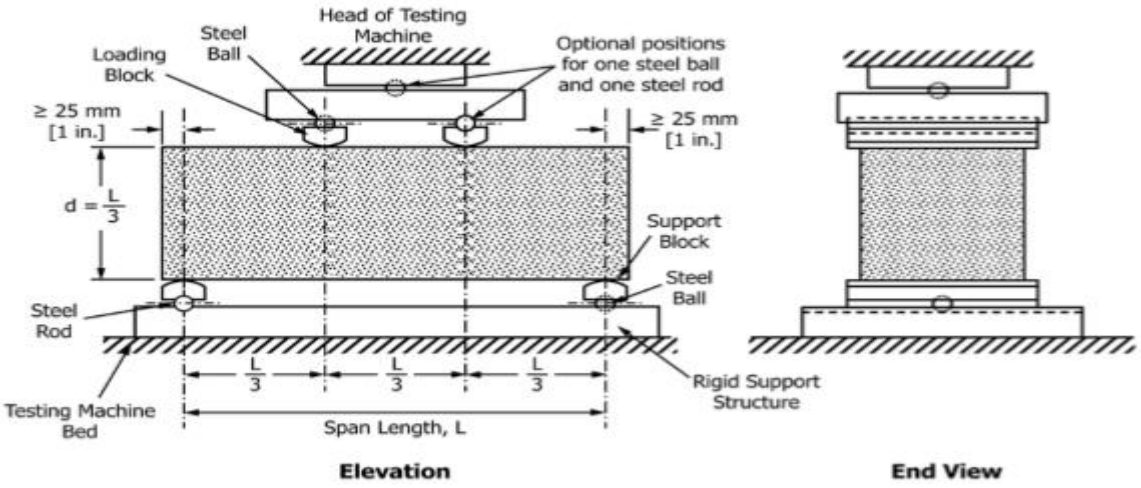


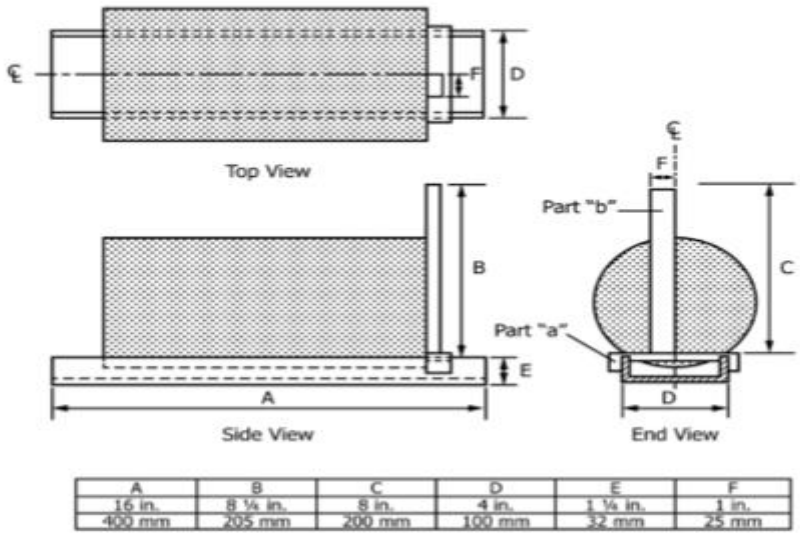
Figure 2. Set up of flexural beam in the testing machine.

2.5.3. Splitting tensile strength

This test was conducted in accordance with ASTM C496 [38]. In this research, 50 mm × 150 mm cylindrical specimens were prepared using a mix ratio of 1:2.36. The specimens were moist cured for the first 7 days followed by 21 days drying at 23°C and 50% relative humidity. At the 28th day, the specimen was place in UTM and tested for its split tensile strength. The load was continuously applied without shock, at a constant rate of 1.4 MPa/min until failure was observed in the specimen. The maximum applied load indicated by the testing machine at failure was recorded and the strength computed. The computation of the splitting tensile strength of the specimen is as follows:

$$T = 2P/\pi ld \quad \ldots\ldots\ldots\ldots (1)$$

Where: T = splitting tensile strength, MPa, P = maximum applied load indicated by the testing machine, N, l = length, mm, and d = diameter, mm. The setup of split tensile strength is shown in Figure 3.



A	B	C	D	E	F
16 in.	8 ¼ in.	8 in.	4 in.	1 ¼ in.	1 in.
400 mm	205 mm	200 mm	100 mm	32 mm	25 mm

Figure 3. Set up of tensile strength of cylindrical specimens in the testing machine

3. RESULTS AND DISCUSSION

3.1. Standard consistency

Table 2 presents the results of standard consistency, initial and final setting time of cement paste when blended with RHA at the various percentages. From the results, it was noticed that the consistency of the mix increased linearly when the cement was partially substituted with RHA. This implies that more SP was added to mix with addition of RHA to achieve a consistent mix conforming to ASTM standard. The disparity in results between OPC and RHA addition can be attributed to the lower specific gravity and higher specific surface area of RHA compared to OPC. The specific gravity and specific surface area of RHA used in this research work were 2.08 and 35.98 m^2/g respectively. As RHA is porous and finer in nature, it will require a higher volume of SP to enhance intrinsic flocculation and further enhance the desired flow ability in the mix. Furthermore, Kartini et al. [39] and Le [40] suggested that the adsorptive properties of cellular RHA particles, combined with their fine texture, result in an increased specific surface area, thus requiring a higher superplastizer. Interestingly, the consistency results obtained align with findings from several researchers regarding the use of similar pozzolanic materials. Regarding the findings recorded by Rao [41] on the use of SF in mortar, they observed a 40% increase in the water requirement when cement was partially substituted with 20 -30 % SF. The control mix consisted of cement mortar without SF. Qing et al. [42] studied the effect of nano silica in mortar, and their outcome revealed higher consistency values for nanosilica mortars in comparison with reference mortars (100 % cement). Khan et al. [43] investigated the

influence of micro silica extracted from RHA. The outcome of their investigation also coincided with the findings by the aforementioned researchers. However, they attributed the outcome of the results to positioning of the finer particles of the RHA in the empty spaces of the cementitious matrix. This leads to the closure of the flow channels in the mix, especially when high volumes of supplements are used. They also recommended that either more water or SP be used to maintain the standard consistency of the mix.

3.2. Initial and final setting time

Figure 4 shows the pattern of setting time behavior of mortars incorporated with RHA at various percentages. From figure 4, it was observed that there was an increase in initial and final setting time with the inclusion of the various percentages of RHA. The initial and final setting of cement mortar when replaced with 10 % RHA was 6.6 hrs, which is lower compared to the reference sample. However, at 20 and 30 % replacement, the setting times (initial and final) increased significantly by 14.6 and 26 hrs, respectively. For similar findings documented by Khan et al. [43], they explained that larger volume of RHA contains SiO_2 that are dormant during its initial phase of cementitious reaction. This invariably means that as the cement is replaced with the various percentages (20 & 30 %) of RHA, the rate of strength gain will reduce and setting time increase. Marthong [44] investigated the effect of RHA on the setting time mortar. The result of his investigation showed an increase in both setting times with increase in RHA content. He attributed the behavior of both the initial and final setting time to the low rate of hydration due to the presence of the RHA. Alshamsi [45] reported an insignificant difference in the setting time of 10 % SF-OPC mortars, and a 6 – 20 % increment for 20 % SF-OPC mortars. Lohtia and Joshi [46] attributed the delay in setting time to theinclusion of SF without using water reducing admixtures in the mix. Other researchers such as Dabai et al. [47], Dakroury and Gasser [16], and Calica [48] also documented similar findings when agro pozzolanic materials were used. However, the work carried out by Rashid et al. [49] yielded a different outcome. Their peak results of initial and final setting time was attained at 15 % replacement with RHA. Beyond 15 %, a drop in setting time was observed. Their obvious reason for the contradiction in results may have been due to the open burning of the ash at an uncontrolled temperature, resulting in the formation of a crystalline RHA ash content. However, there is little or no information available on the comparative influence of crystalline and amorphous RHA on the rheological behavior of RHA mortar.

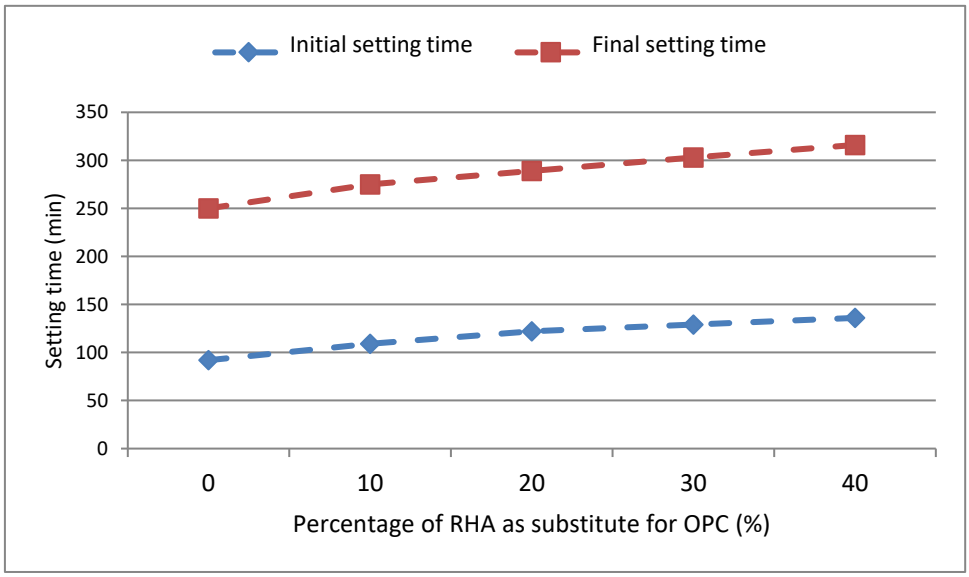


Figure 4. Initial and final setting time of RHA mortars systems

3.4. Fresh density (unit weight), yield, and air content (gravimetric) of fresh mortar

Table 4 presents the results of fresh density of fresh mortar. The density of cement fresh mortar without RHA was higher than density of cement mortar blended with RHA. With increment in the quantity of RHA (at 0 %, 10 %, 20 %, 30 % and 40 %) in the mix (for ratio 1:2.75), there was a percentage reduction in density by 0.2, 0.61, 1.22 and 2.04 %, respectively. This was mainly attributed to the lower density of RHA compared to cement, along with the porous nature of RHA. As RHA partially replaced cement, the resulting cementitious matrix became more porous and less dense. In contrast, for the mix with a ratio of 1:2.36, the observed percentage reductions were 0.12%, 0.61%, 1.45%, and 2.18%. Hence, the blended cement mortar shows a slight decrease in weight compared to the weight of the cement mortar. The decrease can be observed as the percentage of RHA increases from 0% to 40%. This indicates that mortar incorporated with RHA is lighter in weight when used in large quantity.

Table 4. Results of density of fresh RHA mortars (1:2.75 & 1:2.36)

% Binder RHA with cement	For ratio 1:2.75				For ratio 1:2.36			
	Density (Unit weight): kg/m^3	Percent reduction %	Theoretical Density: kg/m^3	Percent reduction %	Density (Unit weight): kg/m^3	Percent reduction %	Theoretical Density: kg/m^3	Percent reduction %
0%	1633.3	0.00	1648	0.00	1593.3	0.00	1628	0.00
10%	1630	0.20	1646	0.12	1590	0.20	1626	0.12
20%	1623.3	0.61	1638	0.61	1580	0.84	1618	0.61
30%	1613.3	1.22	1624	1.45	1573.3	1.26	1604	1.47
40%	1600	2.04	1612	2.18	1566.7	1.67	1592	2.21

3.5. Compressive strength

Figure 5 shows the comparison of strength results of mix ratios 1:2.75 and 1:2.36 for OPC mortar and mortars containing the various percentages of RHA. The results showed that the inclusion of RHA resulted in a mortar with higher strength values compared to the reference (0 % RHA-OPC). The results were also higher at the various curing ages of 7, 14 and 28 days. With respect to mortars of mix ratio 1:2.75 at the 7th day curing period, the maximum strength was attained at 10 % OPC replacement with RHA. The maximum strength was insignificantly higher than the strength of plain mortar by 38.4 %. Beyond 10 % repl., a drop in strength was recorded. However, the strength recorded at 20 % repl. was insignificantly higher than the plain by 1.91 %, while the strength values at 30 and 40 % were lower. For mix ratio 1:2.36, the peak strength was also attained at 10 % repl., with a strength value been 43.5 % higher than the plain. The reason for the gain in strength can be attributed to the fine filler effect of the RHA in the mix, thus resulting to a more improved mortar in terms of strength. The presence of silica content may alsohave had minimal effect on the strength development due to the fact that curing age also plays a significant role in activating the reactive potential of the silica in the $Ca(0H)_2$ to form Calcium Silicate Hydrate (C-S-H).

At the 14thday, the pattern of strength development coincided with that of the 7th day curing period. However, the peak strength recorded at 10 % was higher than that of the 7th day by 29.8 % and 28.1 % for both mix ratios (1:2.75 & 1:2.36). The result of peak strength was higher than that of plain mortar by 47.3 and 59.4 % respectively. The increase in strength can be attributed to the presence of amorphous SiO_2 in 10 % RHA-OPC mortar. According to previous studies by various researchers, the presence of the reactive amorphous SIO_2 in RHA is responsible for further improvement

in the strength performance of the mortar [50,51]. The lower strength results were obtained at 20 and 30 % for both mix ratios may be associated with pozzolanic inactiveness of the larger percentage of RHA. It may also have been possible that at these higher percentages (20 % of RHA), agglomeration may have occurred in the matrix due to oversaturation and improper dispersion of RHA. This can lead to a reduction in hydration and the formation of a porous gel structures, thus affecting negatively the strength behavior of the mortar matrix [52].

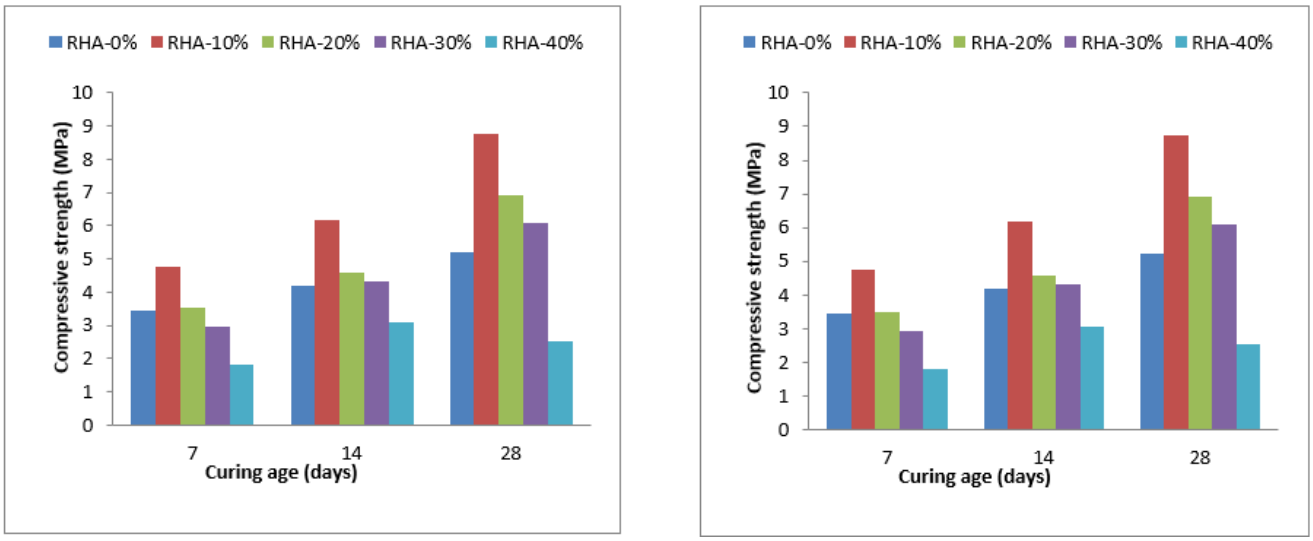


Figure 5. Compressive strength behavior of RHA mortars systems at the 7th, 14th and 28th curing.

At the 28th day curing period, the maximum strength was recorded at 10 %, with result valuesof 8.759 and 10.252 Mpa for mix ratios 1:2.75 and 1:2.36 respectively. The results were higher than the strength of plain mortar by 68 % and 67.1 %. Hence, the strength results obtained at 10 % and 28 days curing age falls within the specification of ASTM C618 [6] of strength activity index (ASTM C311 [53]) for cement substituting pozzolanic materials. According to ASTM C618 [6], the compressive strength of mix containing partially substituted pozzolanic materials should be 65 % of the corresponding OPC mortar at 28 days. According to ASTM C311 [53], the strength activity index values are mainly calculated to evaluate reactivity of mineral admixtures with the cement.

The pattern of strength development also tallied with findings by Lima et al. [54] and Cavalcante et al. [55]. They studied the influence of silica extracted from RHA on strength development in cementitious mortar. They observed an increment in strength with the addition of 5% and 16% silica. They also associated the improvement in strength to the high fineness and reactivity of RHA in the matrix resulting in the formation of more cementitious gel (C-S-H), and subsequently decreasing the amount of C-H in the matrix. Gastaldini et al. [56] indicatedan increase in compressive strength with RHA; they recorded the maximum strengths at 15 %. Hwang et al. [57] and Isai et al. [18] reported a decrease in compressive strength with RHA addition up to 30 %. Finding by Khan et al. [58] recommended the use of 30% of RHA for optimal compressive strength performance in marble-based cement mortars while Shahas et al. [59] showed that the combination of GGBS and RHA of 70 and 30% inclusion produces mortar of strength higher than plain mortars. The stress strain behaviors of mortars of mix proportions 1:2.75 and 1:2.36 for the various percentages of RHA under compression are presented in Figure 6 . Upon application of a compressive loading, the stress-strain values increase exponentially with peak results attained at all replacement levels. For mortars of both mix proportions cured at 7, 14 and 28 days, the maximum stress-strain was achieved at 10% RHA. However, the stress strain results values of mix proportion 1:2.75 was significantly higher than that of 1:2.36 respectively.

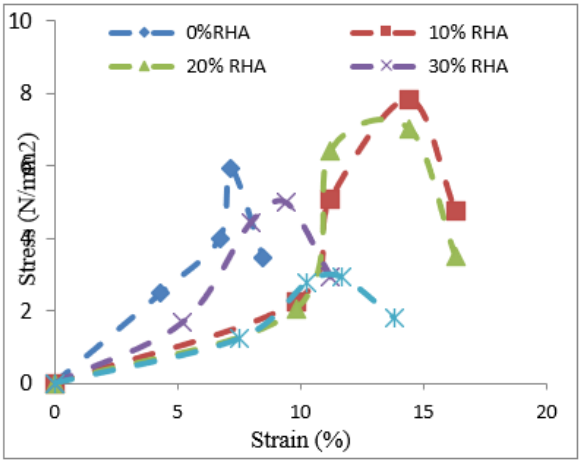


Figure 6. Stress-strain at the 7th day curing age (Mix ratio; 1:2.75)

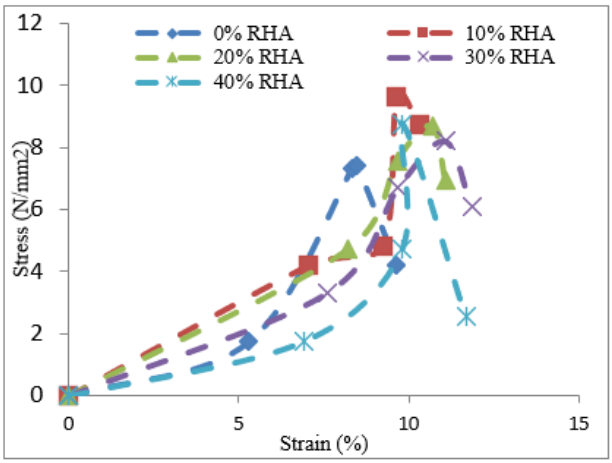


Figure 7. Stress-strain at the 14th day curing age (Mix ratio; 1:2.75)

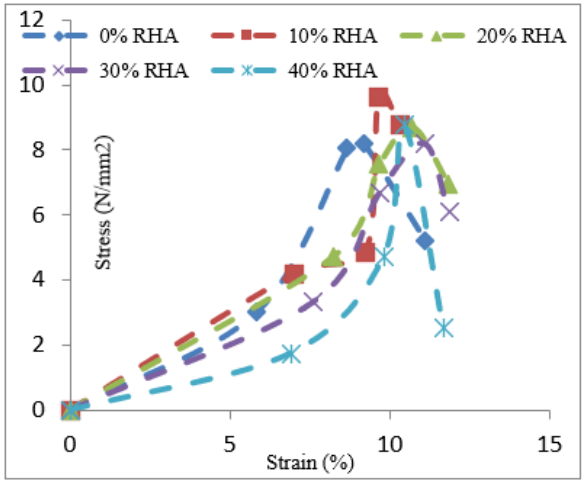


Figure 8. Stress-strain at the 28th day curing age (Mix ratio; 1:2.75**)**

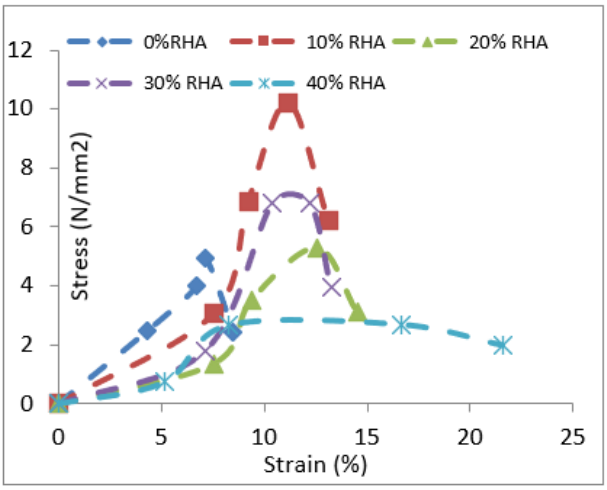


Figure 9. Stress-strain at the 7th day curing age (Mix ratio; 1:2.36)

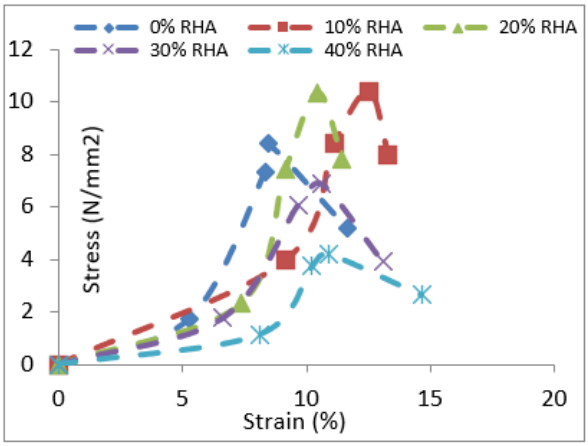


Figure 10. Stress-strain at the 14th day curing age (Mix ratio; 1:2.36)

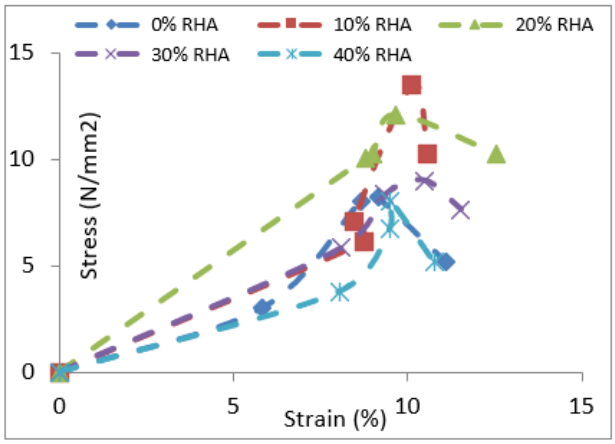


Figure 11. Stress-strain at the 28th day curing age (Mix ratio; 1:2.36

3.6. Splitting tensile and flexural strength

The flexural and tensile performance of Mortar embedded with RHA was determined with reference to the mix that gave the ultimate compressive strength. Hence, in this case, 10% RHA mortars at a mix ratio 2.36 and curing age of 28 days was adopted; and the results for both the split tensile and flexural strength are presented in Table 5. Based on the outcome, the flexural strength of the 10% RHA mortars was 22.5 % greater than that of the plain mortar. This result tallied with the findings recorded

by Jamil et al. [27]. However, Habeeb and Fayyadh [60] documented that the size of the RHA plays a significant role in strength development, as a reduction in the size leads to an improvement in mortar strength. Zhang et al. [61] buttressed on Habeeb and Fayyadh [60] findings; the finer RHA stirs up pozzolanic reaction and acts as fillers. Awash [62] obtained its optimum flexural strength at 20% RHA (Blaine fineness 11200cm^2/g).For the split tensile strength, an ultimate strength of 9.245 Mpa was recorded. This was higher than the strength of the plain by 9.6 %.

Table 5. Split tensile and flexural strength of RHA mortars (10% RHA mortars at mix ratio 2.36 and curing age of 28 days)

Test No.	Splitting tensile strength	Flexural strength
1	12.129	4.392
2	11.013	5.318
3	4.591	4.530
Mean	9.245	4.746

However, Khassaf al. [63] also recorded a peak tensile strength 15.4% at 10 % repl. and at 28 days curing. Higher results values greater than plain mortar incorporated with 20 RHA was attained 56 days curing. Furthermore, the outcome of investigations conducted by Le et al. [40] and Foong et al. [64] showed an increase in tensile strength RHA mortar by 17.65 and 28 %, of plain mortar; their peak strengths were obtained at 15 % replacement. Findings recorded by Talsania et al. [65], Bansal et al. [66] showed an optimal tensile strength at 10% RHA, with their water to binder ratio varying from 0.3-0.45 without the use of SP. Adenuga et al. [67] adopted the use of SP to achieve it optimal water to binder ratio and strength performance at 0.6 and 10 %. Higher optimal RHA repl. of 15 and 20 % were recorded by Ganasan et al. [68], Mahmud et al. [69], Kartini et al. [39].

4. CONCLUSION

The research was conducted to evaluate the effect of RHA on the performance of cement mortars by partially replacing the OPC with RHA at 10%, 20%, 30% and 40%. Prior to the investigation, the RHA was calcined in a blast furnace at a controlled temperature and time of 600^{o}c and 6 hrs, to obtain amorphous silica content. The influence of partially replacing OPC with RHA on the fresh (standard consistency, initial and final setting, and Fresh density (unit weight), yield, and air content (gravimetric) of fresh mortar) and hardened properties (Compressive, tensile and flexural behavior) were investigated with reference to plane cement mortar (0% RHA).Based on the investigation, the main findings are summarized as follows:

1. An increase in standard consistency was recorded with an increase in the amount of RHA. This can probably be attributed to the specific gravity (2.08) and specific surface area (35.98m^2/g) of the RHA, which is higher than that of OPC; as a result, more water is required to achieve a standard flow. Also, the initial and final setting times increased with addition of RHA, with a resultant increment of 6.6%, 14.6% and 26 %. The density of fresh cement mortar was also greater than the blends (10%, 20%, 30% and 40%) for both binder to aggregate mix ratios of 1:2.95 and 1:2.36. For mix ratio 1:2.95, the density decreased by 0.2%, 0.61%, 1.22% and 2.04%. For mix ratio 1:2.36, the density decreased by 0.12%, 0.61%, 1.45 and 2.18%. Hence, it's worthy to note that the inclusion of RHA resulted in a mortar of lighter weight.
2. The maximum compressive was attained at 10%RHA at the 28 day curing age, for both binder to aggregate mix ratio of 1:2.36 and 1:2.95. A result of 8.759 and 10.252, which is greater than the plain mortar by 68% and 67%, was documented. Beyond 10% RHA, a decrease in compressive strength by 8.5%, 13.3% and 19.4% were recorded. The reason for the decrease can possibly associated with agglomeration and improper dispersion of RHA particles, thus delaying the hydration and also resulting in a weaker

hardened mortar.The result of tensile and flexural strength recorded was 9.245 Mpa and 4.746 Mpa at the selected 10%RHA and a binder to aggregate ratio of 1:2.36. The selection was based on the fact that a maximum compressive strength was achieved at the aforementioned binder to aggregate ratios and cement replacement levels. The results obtained for both tensile and flexural strength was higher than the strength of control mortar by 9.6% and 22.5% respectively.

FUNDING/SUPPORT

Not mentioned any Funding/Support by authors.

ACKNOWLEDGMENT

Not mentioned by authors.

AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

NFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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